MONTE-CARLO MODELING OF EXTINCT SHORT-LIVED R-PROCESS RADIOACTIVITIES. B. S. Meyer, N. Luo, *Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, brad@cosmo.phys.clemson.edu*.

The recently discovered evidence[1,2] for live ^{182}Hf in the early solar system opens up important new possibilities for constraining time scales for r-process nucleosynthesis in the Galaxy[3]. The fascinating puzzle that emerges is that ^{182}Hf does not "fit" with the other short-lived r-process radioactivities. From one point of view, the inferred ^{182}Hf/^{180}Hf value in the early solar system, $\sim 3 \times 10^{-4}$, agrees well with the value one estimates to be present in molecular cloud cores[3]. The problem is that in this case the other r-process radioactivities have meteoritic values much larger than their steady synthesis values in molecular clouds[3,4]. On the other hand, allowing a long free-decay interval for steady-state ^{129}I to reach its meteoritic value would give too little ^{182}Hf. An obvious conclusion would be that the r-process yields of the short-lived radioactivities can vary from supernova to supernova.

For varying yields to be the explanation of the non-steady-state abundances of the short-lived r-process radioactivities, contributions from individual supernovae must play a crucial role. In this case, we must find some way of following the individual supernovae. To do this, we have chosen to make Monte Carlo calculations of the galactic evolution of the abundances of the r-process short-lived radioactivities and the stable reference isotopes ^{107,108}Pd, ^{129,127}I, ^{182,180}Hf, and the ^{244}Pu-^{238}U pair. We modeled a large part of the Galaxy as a string of 30 regions, each region containing 10^8 solar masses. We think of the total 3×10^9 solar masses as an annulus comprising 3% of the Galaxy. Each region contained a hot zone, a warm zone, and a molecular cloud lying completely within the warm zone. Each region communicated with its neighbors via their hot zones on a time scale of 10^7 years. Material also moved from hot zone to warm zone and from warm zone to molecular cloud on time scales of 5×10^7 years.

We took the average Galactic rate of supernovae over the course of the Galaxy's history to be one supernova every 30 years. From the solar system's mass fractions of ^{108}Pd, ^{127}I, ^{180}Hf, and ^{238}U, the r-process production ratios of the radioactive species, and from corrections for contributions from the s-process, we estimated the average yield of the relevant species from each supernova. We then took the average Galactic supernova rate near the time of the solar system's formation (which we took to be 10^{10} years after Galaxy formation) to be one (r-process producing) supernova every 300 years. Our reasoning here is that the star formation rate in galaxies falls with time on a time scale of $\sim 3 \times 10^9$ years (see e.g. [5]). Thus, the supernova rate at the time of solar system formation is smaller than the average. With a Galactic supernova rate of one every 300 years, we have on average one supernova every 10000 years in our annulus. For our Monte Carlo calculation, we lay down supernovae randomly in warm zones in the annulus, distributed in time in agreement with Poisson statistics. We evolve the system over the last 6×10^8 years before solar system formation, which means we follow $\sim 6 \times 10^4$ supernovae in the annulus. At 10^{10} years, we record the ratios of radioactive to stable or long-lived species in each molecular cloud.

In our first calculation, we assumed all supernovae produce the same amount of r-process nuclei and the nuclei are made in their solar proportions. Figures 1-4 show the distribution of the the various r-process ratios among the molecular clouds at time 10^{10} years after Galaxy formation. The ratios for ^{107}Pd/^{108}Pd and ^{129}I/^{127}I are within a factor of $\sim$ two of the values inferred to be present in our solar system at its formation (denoted for each case by the arrow). The agreement results because we have a low (r-process producing) supernova rate near solar system formation. Clearly the ^{182}Hf/^{180}Hf and ^{244}Pu/^{238}U ratios do not agree with the suggested solar system values of 3×10^{-4} and 7×10^3, respectively. A larger supernova rate (e.g. the canonical rate) could solve this problem but would throw off the other two ratios.

In an attempt to get the ^{182}Hf and ^{244}Pu consistent with ^{107}Pd and ^{129}I, we followed the suggestion of [3] that r-process yields may vary from supernova to supernova. We assumed that all of our supernovae made Pd and I, but that certain rare ones (we took these to be 1% of all supernovae) were the dominant producers of Hf, U, and Pu. Of course these rare supernovae had to have enhanced yields in order to account for the solar system's supply of stable Hf and long-lived ^{180}Hf. We took this enhancement factor to be 90. Thus the rare supernovae produce 90% of all r-process Hf, U, and Pu. The idea is that on average the ^{182}Hf will be low with respect to the putative meteoritic value, but some molecular cloud or clouds, by virtue of fluctuations in the rate or location of supernovae, might have a ^{182}Hf/^{180}Hf ratio near 3×10^{-4}. Figures 5-8 show the results of this calculation. There is more of a spread in the Hf ratio, but no cloud is close to having a ratio of 3×10^{-4}. Similarly, the ^{244}Pu fails, although there is slightly more spread to the distribution.

Our conclusion is that it is indeed very difficult to reconcile a large ^{182}Hf/^{180}Hf ratio with that for the other r-process radioactivities. It may be that Hf-producing supernovae are even rarer than we have considered here or that other mixing time scales and supernova rates are more appropriate. We are pursuing further Monte Carlo calculations to explore these possibilities.

References:

[1] Lee, D.-C. and Halliday, A. N. (1995) Nature, 378, 771-774.

[2] Harper, C. L. (1996) GCA, 60, 1131-1153.

[3] Wasserburg, G. J., Busso, M., and Gallino, R. (1996), Astrophys. J. Lett., 466, L109-L113.

[4] Harper, C. L. (1996) Astrophys. J., 466, 1026-1038.

[5] Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Streidel, C. C., and Fruchter, A. (1996) Mon. Notices Roy. Astron. Soc., 283, 1388-1404.

MONTE-CARLO GALAXY EVOLUTION: Meyer and Luo

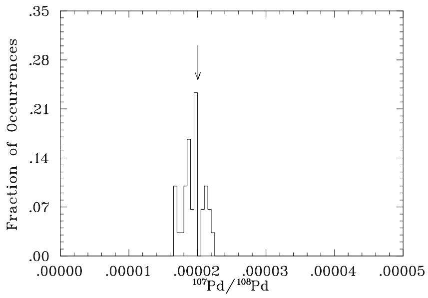

Figure 1

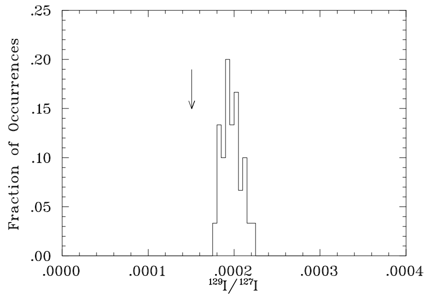

Figure 2

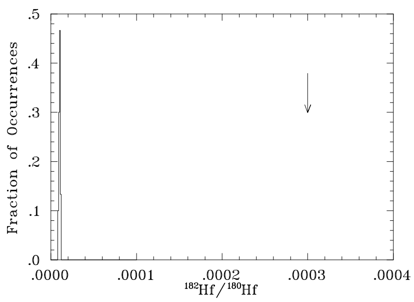

Figure 3

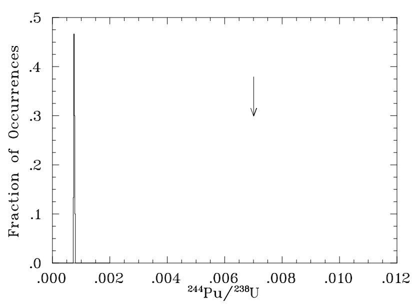

Figure 4

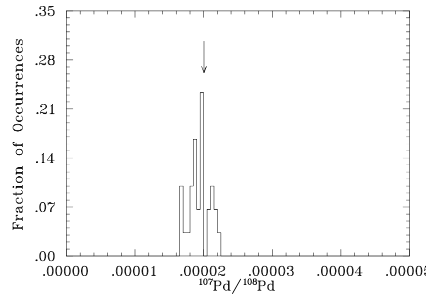

Figure 5

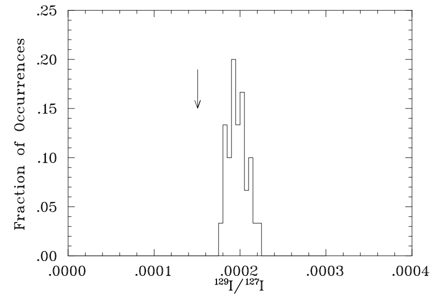

Figure 6

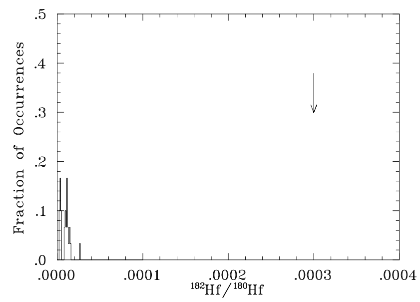

Figure 7

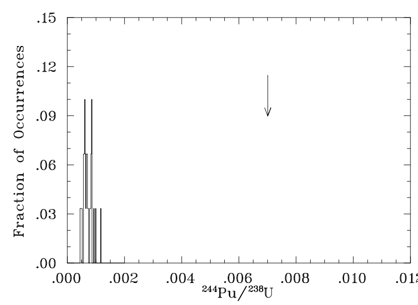

Figure 8